

National Aeronautics and Space Administration  
Jet Propulsion Laboratory  
California Institute of Technology

# **Impact of Acoustic Standing Waves on Structural Responses: Reverberant Acoustic Testing vs. Direct Field Acoustic Testing**

Presented by:

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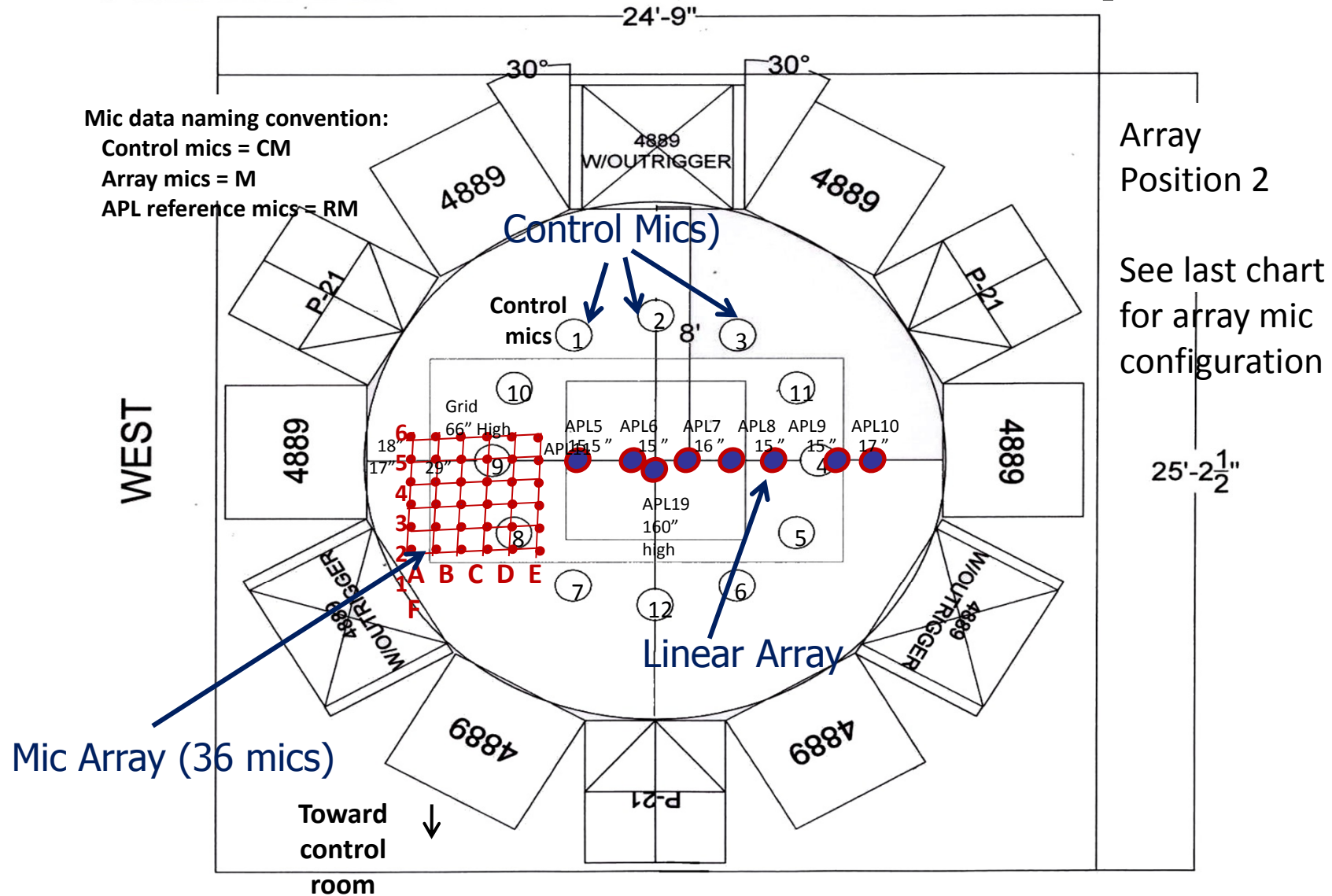
*The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.*

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# Overview

- The aerospace industry has been using two methods of acoustic testing to qualify flight hardware
  - Reverberant Acoustic Test (RAT)
    - Many tests performed over the last several decades
  - Direct Field Acoustic Test (DFAT)
    - Over 100 tests performed in the last decade
- The acoustic field obtained by RAT is generally understood and assumed to be diffuse, except below Schroeder cut-off frequencies
- DFAT method of testing has some distinct advantages over RAT, however the acoustic field characteristics can be strongly affected by test setup such as the speaker layouts, number and location of control microphones, and control schemes
- In this paper the following are discussed based on DEMO tests performed at APL and JPL:
  - Acoustic wave interference patterns and acoustic standing waves
  - The structural responses in RAT and DAFT
- Summary and recommendations

# APL DEMO Test Setup

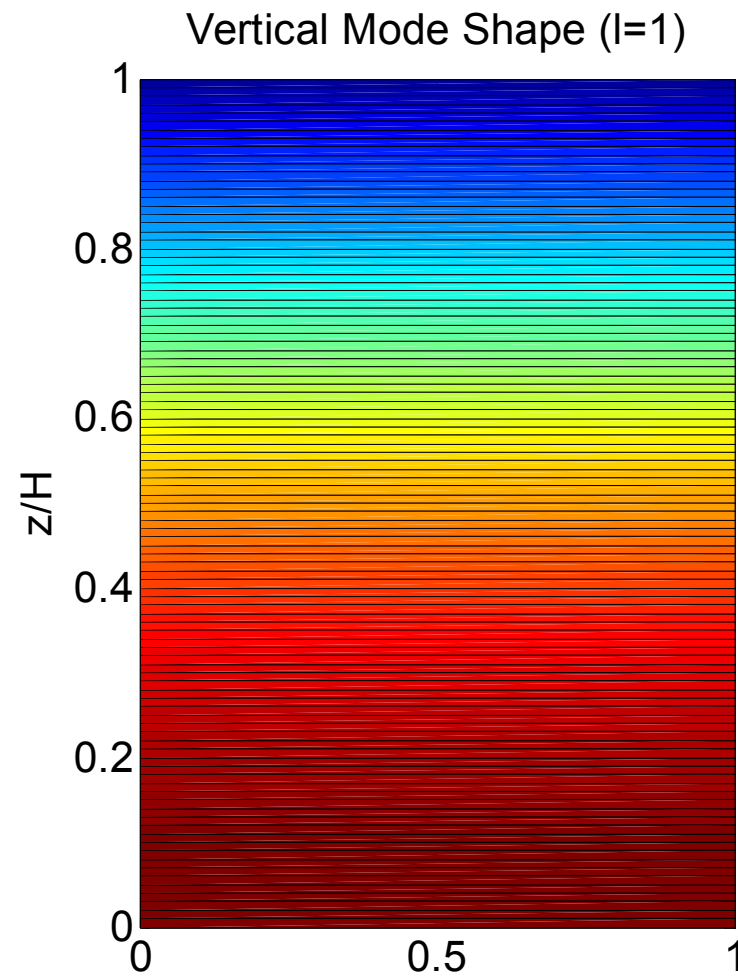
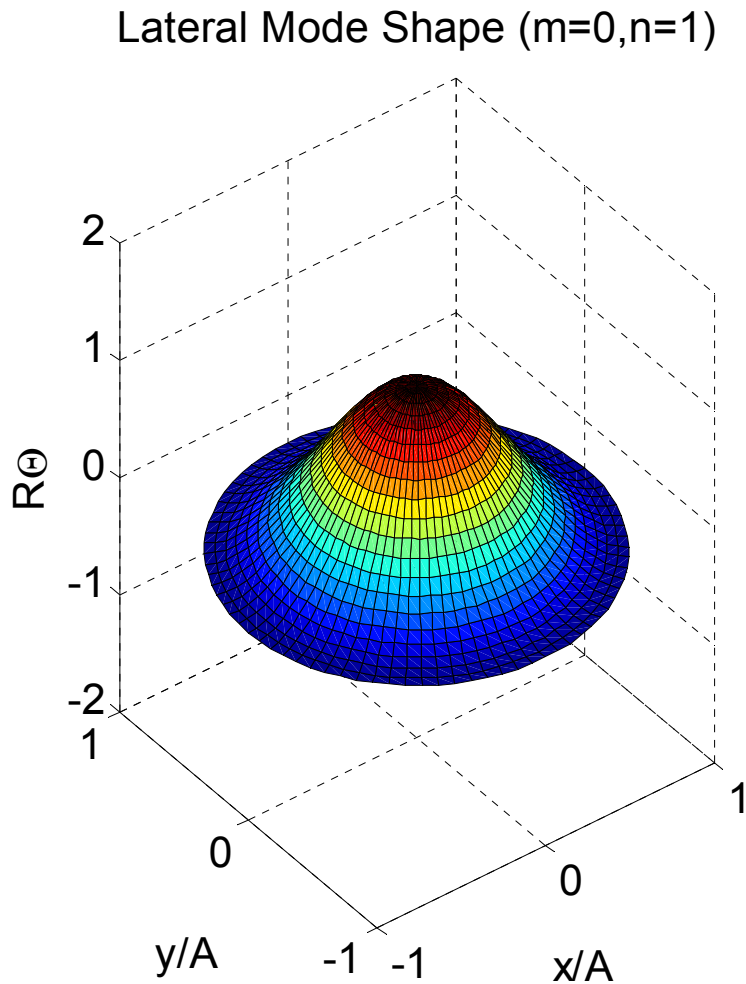


# **Acoustic Standing Waves vs. Interference Wave Patterns**

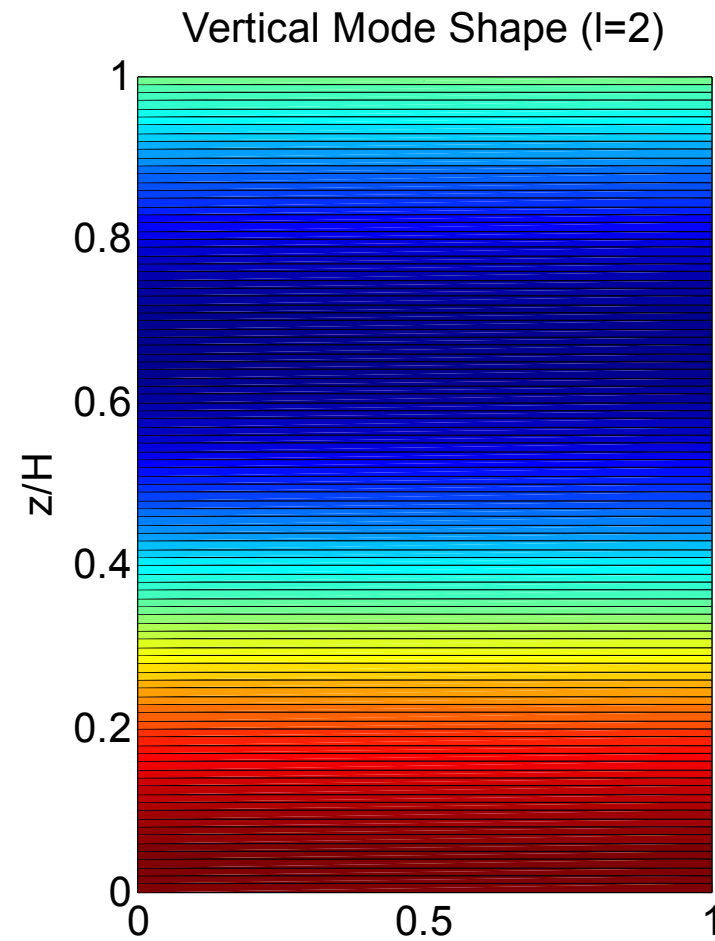
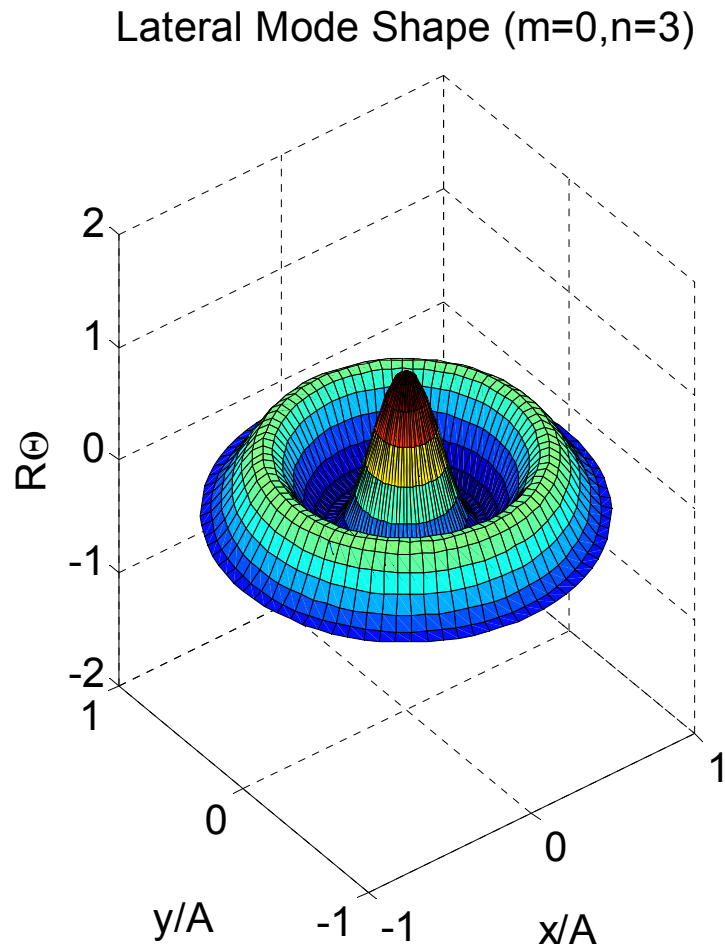
# Theoretical Model

- **Model DFAT interior as cylindrical cavity,  $P(r, \theta, z)$** 
  - Radius,  $A = 8 \text{ ft (2.44 m)}$
  - Height,  $H = 150 \text{ in (3.81 m)}$
- **Boundary conditions**
  - Rigid at speaker faces and ground
    - $(\delta P / \delta r)_{r=A} = (\delta P / \delta z)_{z=0} = 0$
  - Pressure release at top
    - $P_{z=H} = 0$
- **Mode orders ( $lmn$ )**
  - $l$ , vertical ( $z$  direction)
  - $m$ , angular ( $\theta$  direction)
  - $n$ , radial ( $r$  direction)

# Predicted cylindrical cavity mode 101, 88 Hz



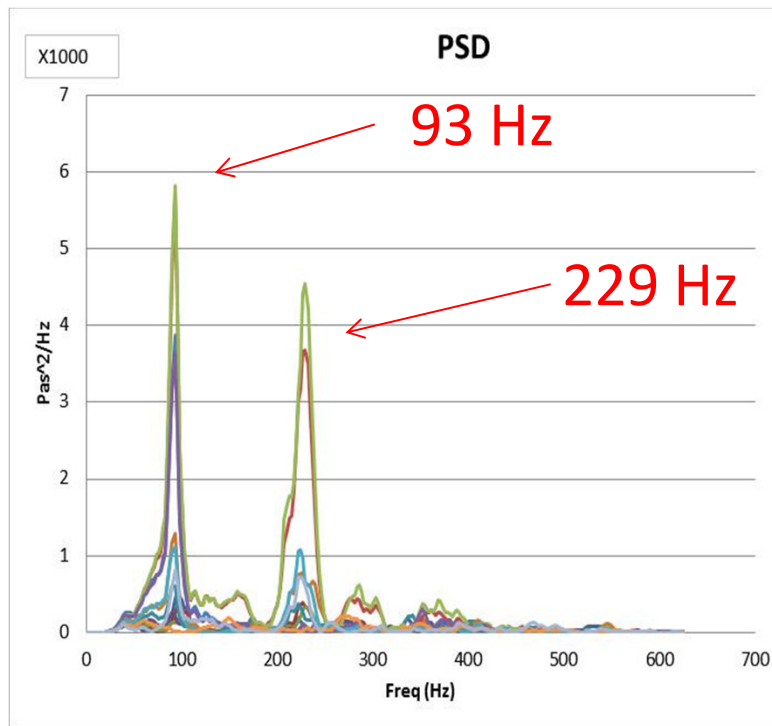
# Predicted cylindrical cavity mode 203, 237 Hz



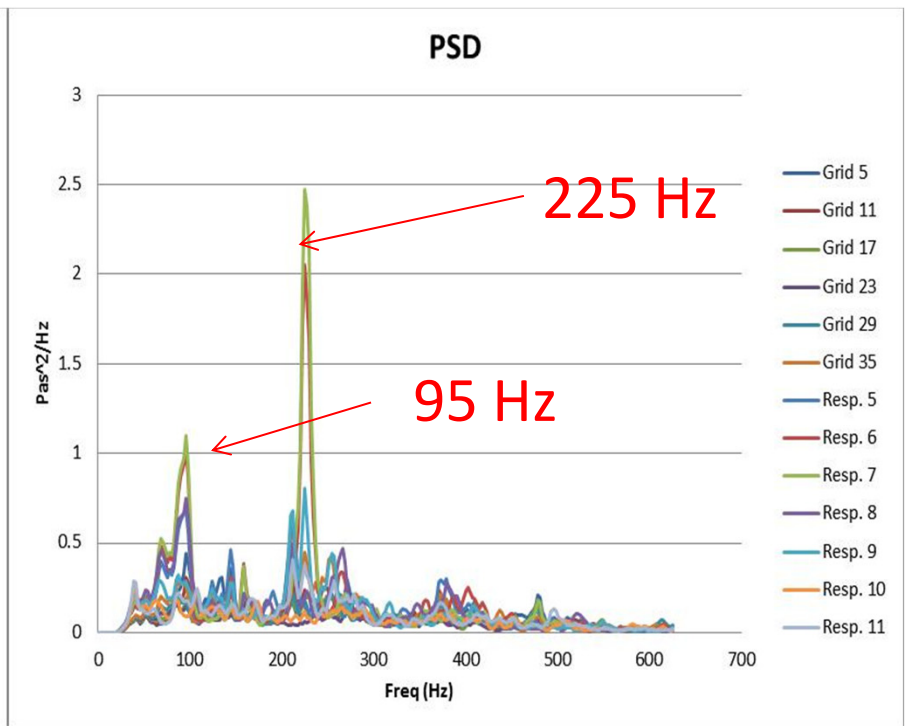
# APL Demo Test (No Test Articles)

## Acoustic Standing Modes (SISO vs MIMO)

**SISO**



**MIMO**



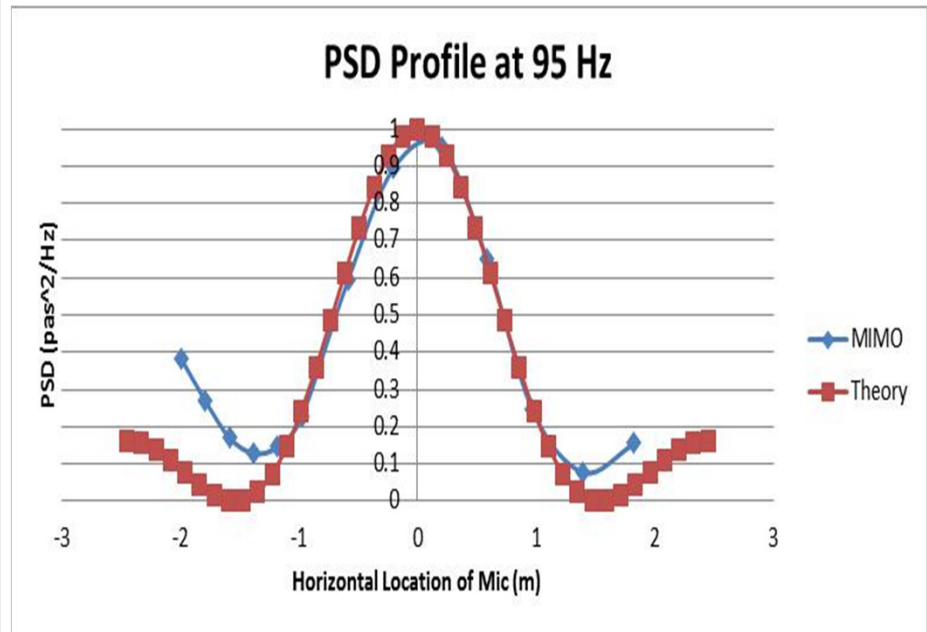
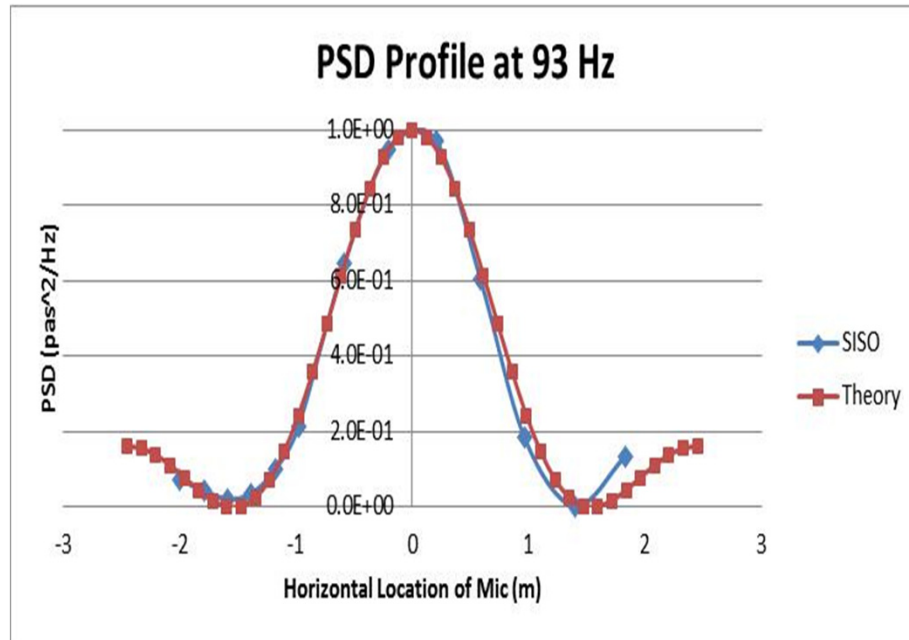
**Sound pressure spectra (Pa<sup>2</sup>/Hz) computed using the linear microphone array: ~93 Hz and ~229 are the dominant acoustic modes (similar for SISO and MIMO control schemes)**



# Acoustic Standing Wave Mode 101 (Radial)

**SISO**

**MIMO**

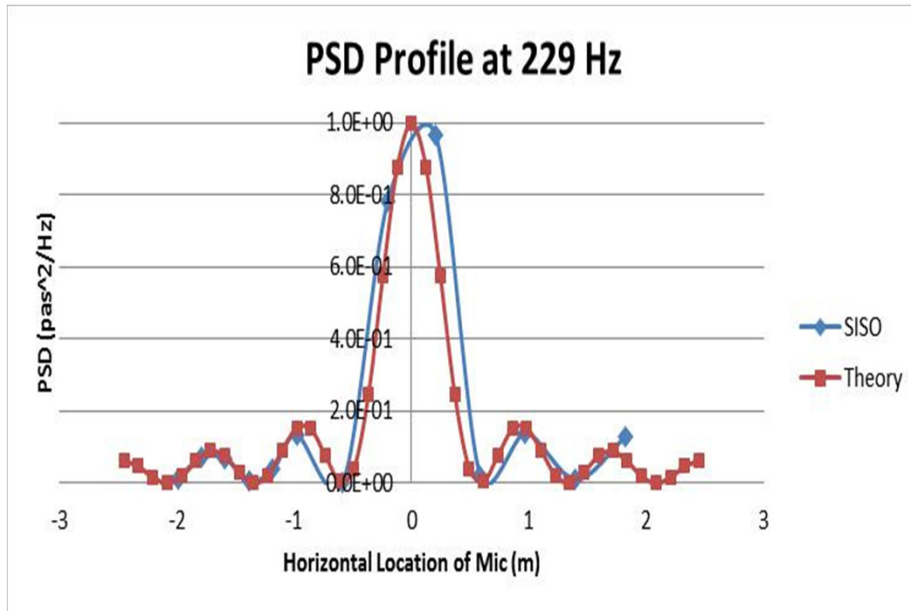


**Predicted 89 Hz and Measured 93 Hz    Predicted 89 Hz and Measured 95 Hz**

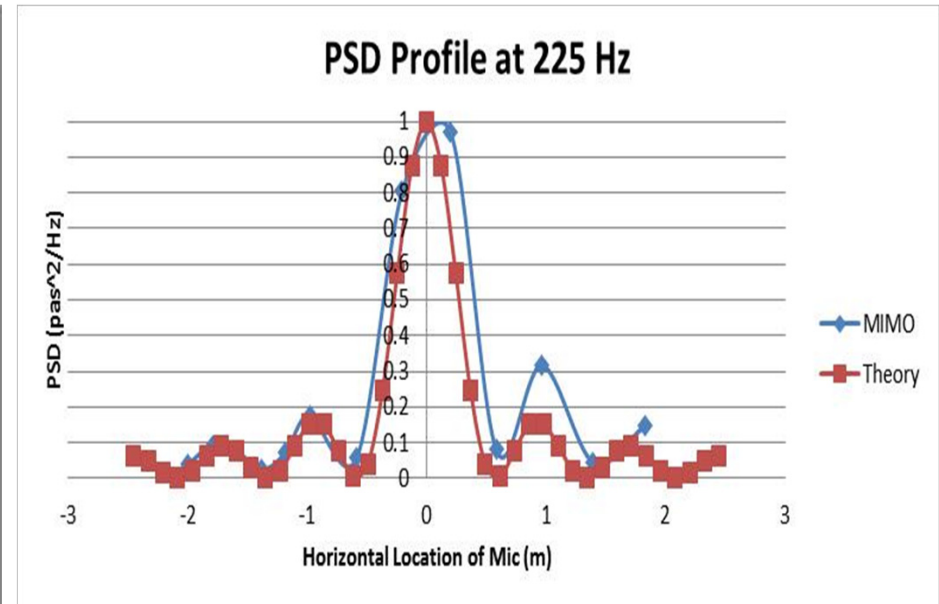
**Acoustic Standing Wave not dependent on how the acoustic field  
within the speakers is controlled; it is a function of the speakers  
setup geometry**

# Acoustic Standing Wave Mode 203 (Radial)

**SISO**



**MIMO**

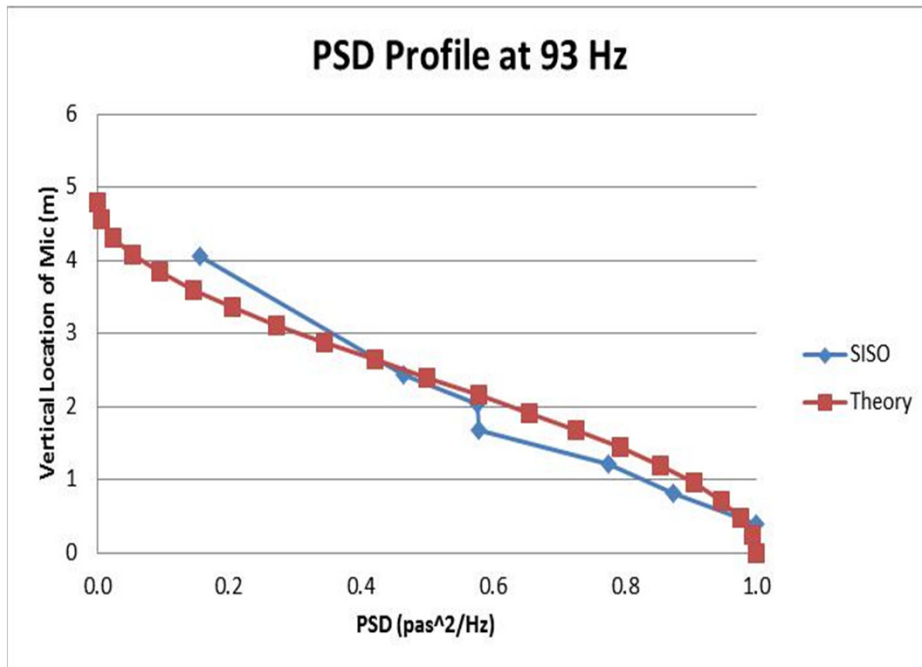


**Predicted 239 Hz and Measured 229 Hz      Predicted 239 Hz and Measured 225 Hz**

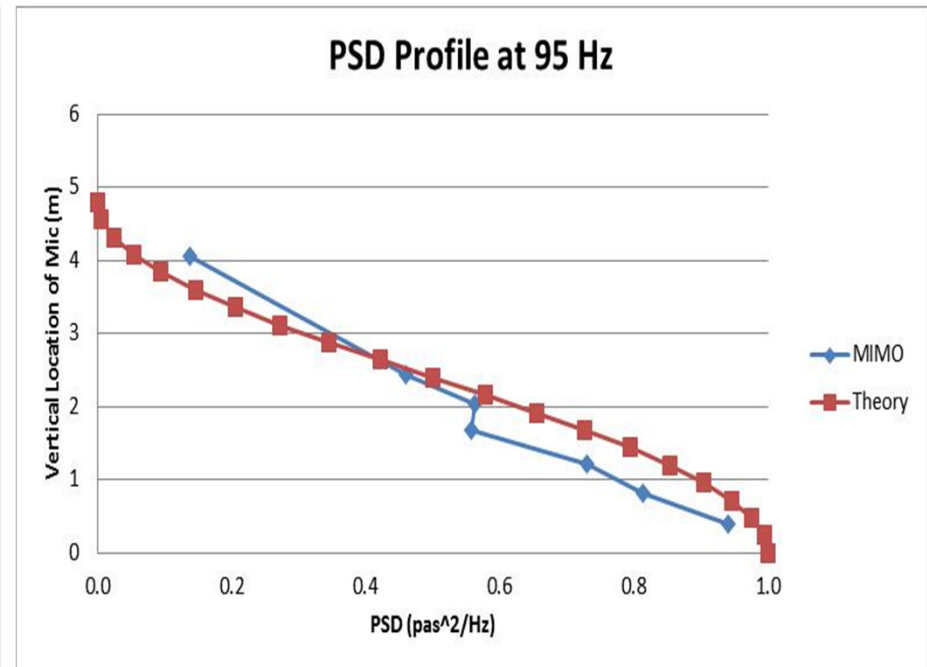
**Acoustic Standing Wave (Mode 203) not dependent on how the acoustic field within the speakers is controlled; it is a function of the speakers setup geometry**

# Acoustic Standing Wave Mode 101 (Vertical)

**SISO**



**MIMO**



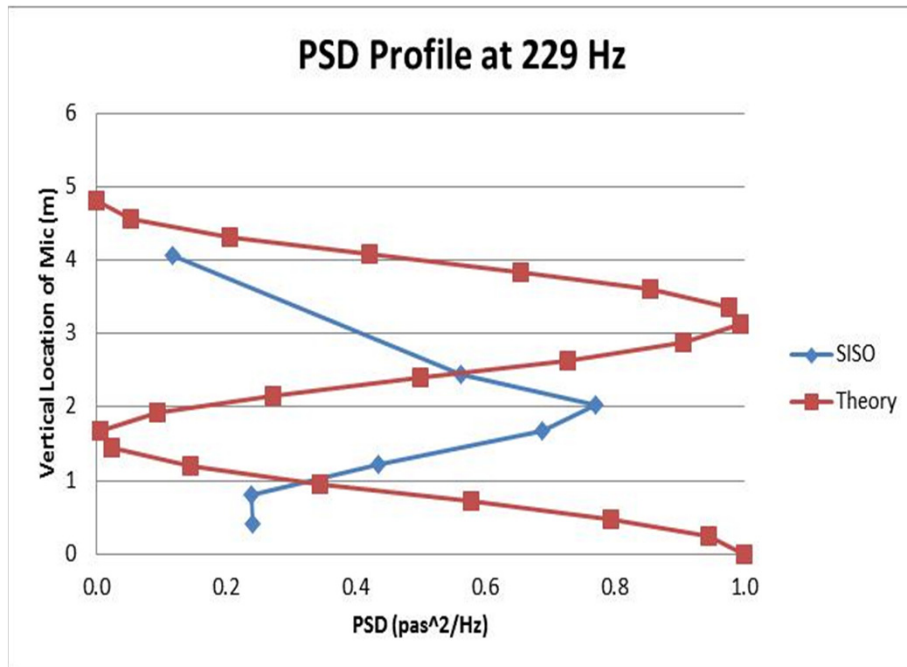
**Predicted 89 Hz and Measured 93 Hz**

**Predicted 89 Hz and Measured 95 Hz)**

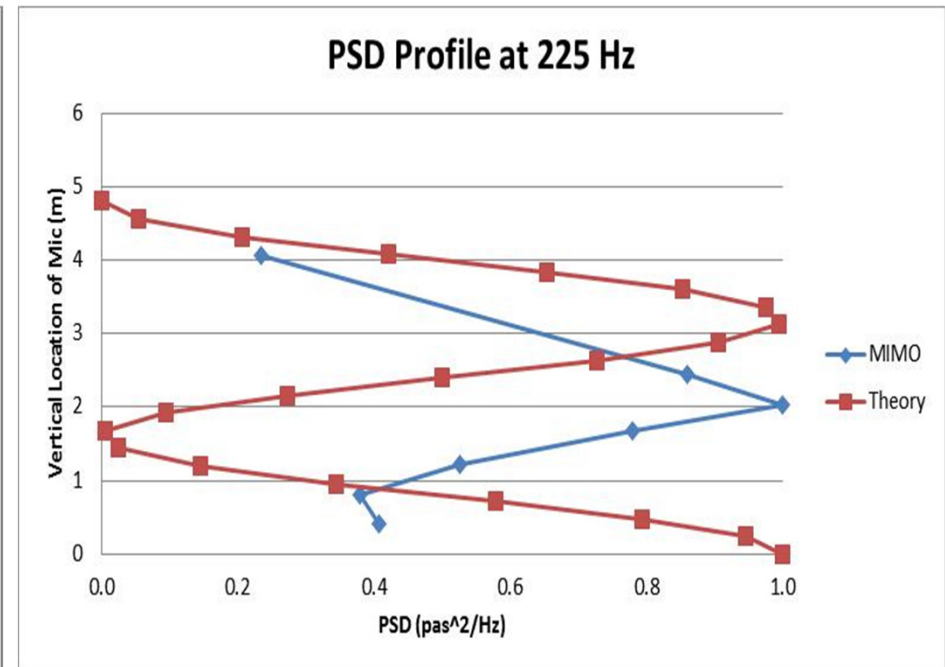
**Acoustic Standing Wave (Mode 101) not dependent on how the acoustic field within the speakers is controlled; it is a function of the speakers setup geometry**

# Acoustic Standing Wave Mode 203 (Vertical)

**SISO**



**MIMO**



**Predicted 239 Hz and Measured 229 Hz**

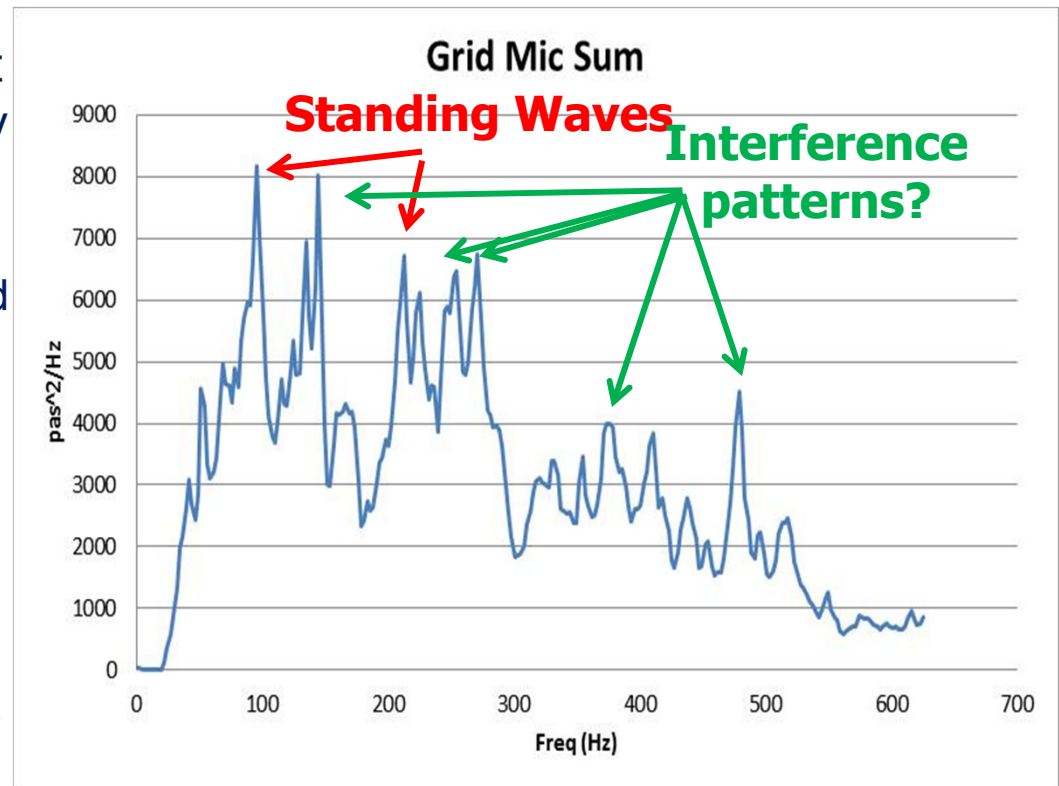
**Predicted 239 Hz and Measured 225 Hz**

**Acoustic Standing Wave (Mode 203) not dependent on how the acoustic field within the speakers is controlled; it is a function of the speakers setup geometry**

**Differences in the predicted and measured vertical mode may be due to the complex sound field near the top of the speakers**

# Why Acoustic Standing Waves Matter?

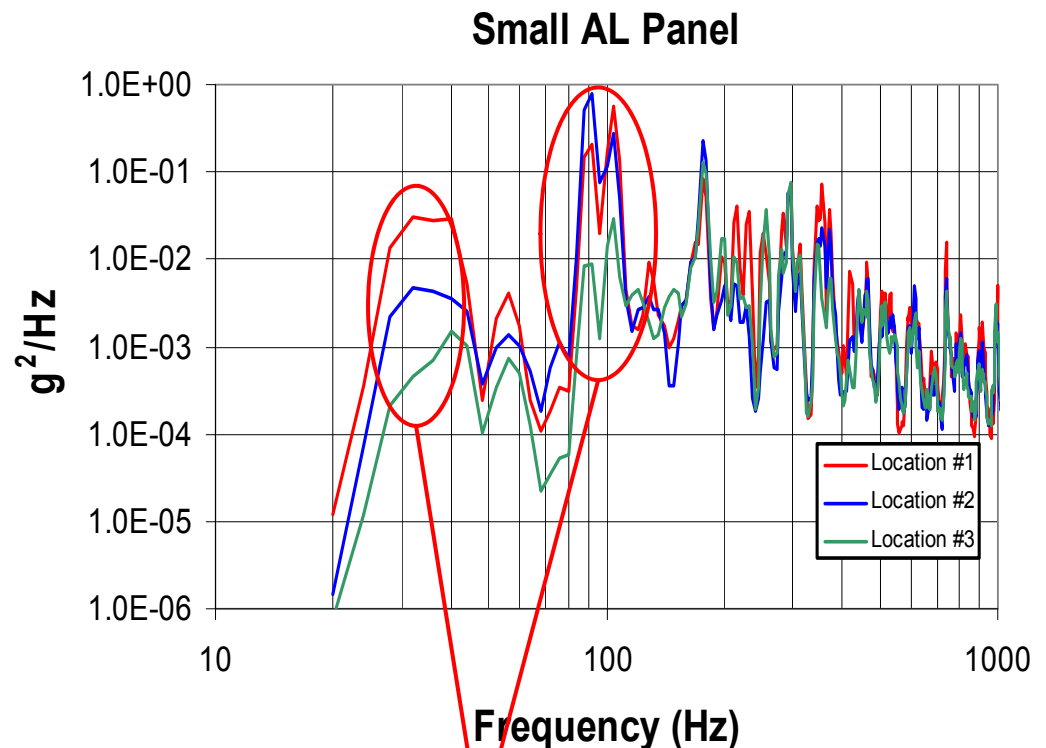
- Interference wave patterns and acoustic standing waves are part of the acoustic field generated by DFAT
  - Interference patterns provide peaks and valleys within the field and are affected by control schemes
    - structural responses consistent (i.e. peaks increase and valleys decrease the responses)
  - Standing waves, on the other hand, could significantly impact structural responses and are not affected by control schemes
    - Understanding these waves within DFAT field is very important (See next chart)



# Chamber/Structural Modal Coupling

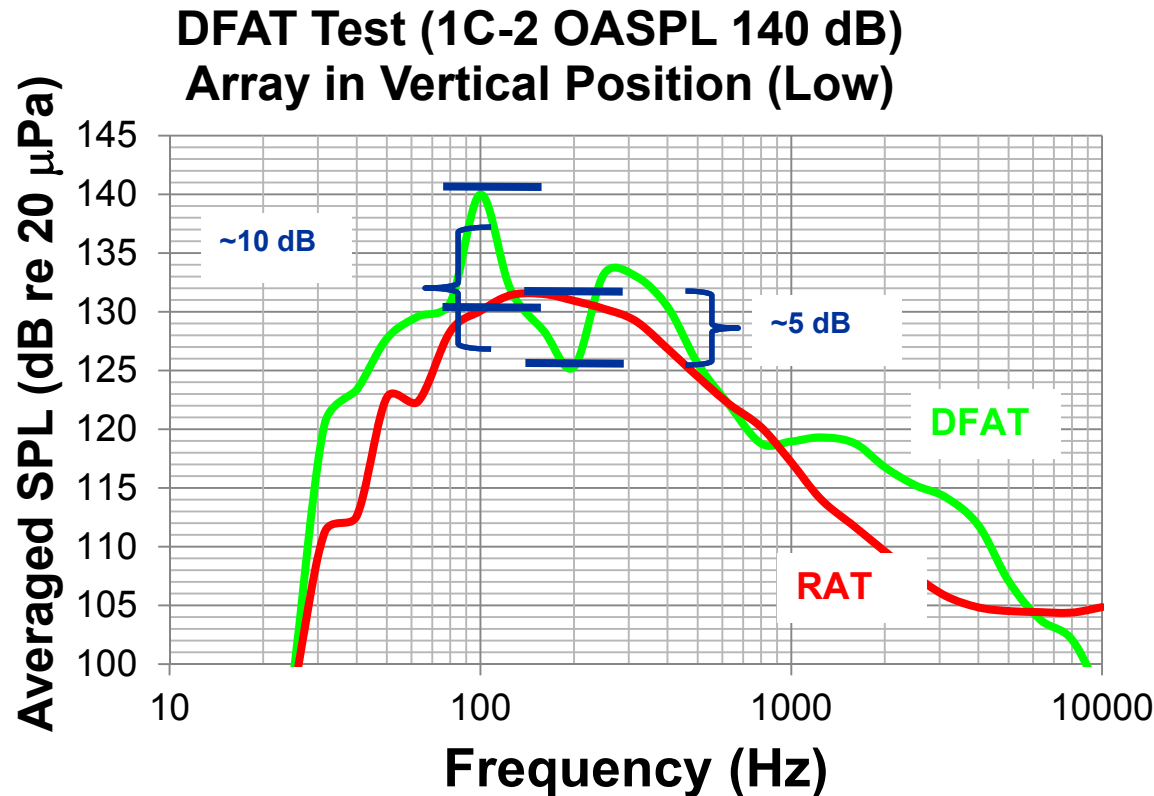
(Panel Response Accelerations)

- 1/4" AL panel placed at three locations in the chamber
  - ~ Middle, 114 inches from one of the wall (location #1)
  - ~ 50" from the wall (location #2)
  - ~ 14" from the wall (location #3)
- Acoustic/Structural Coupled Frequencies:
  - ~31 Hz and 92 Hz (coupled with chamber mode perpendicular to the panel)
    - 31 Hz: 10 dB difference in pressure levels and 18 dB in structural responses
    - 92 Hz: ~ 2 dB difference in pressure levels and 20 dB in structural responses
  - 56 Hz and 104 Hz coupled with chamber other modes in two other directions
  - Structural responses of the mode at 176 Hz unchanged



**Acoustic standing waves/ Structural modal coupling could cause 20+ dB increase in structural responses; attention must be given to this phenomenon in DFAT testing**

# JPL Demo Test: Sound Pressure Levels: DFAT (SISO) and RAT Comparisons Using Microphone Array



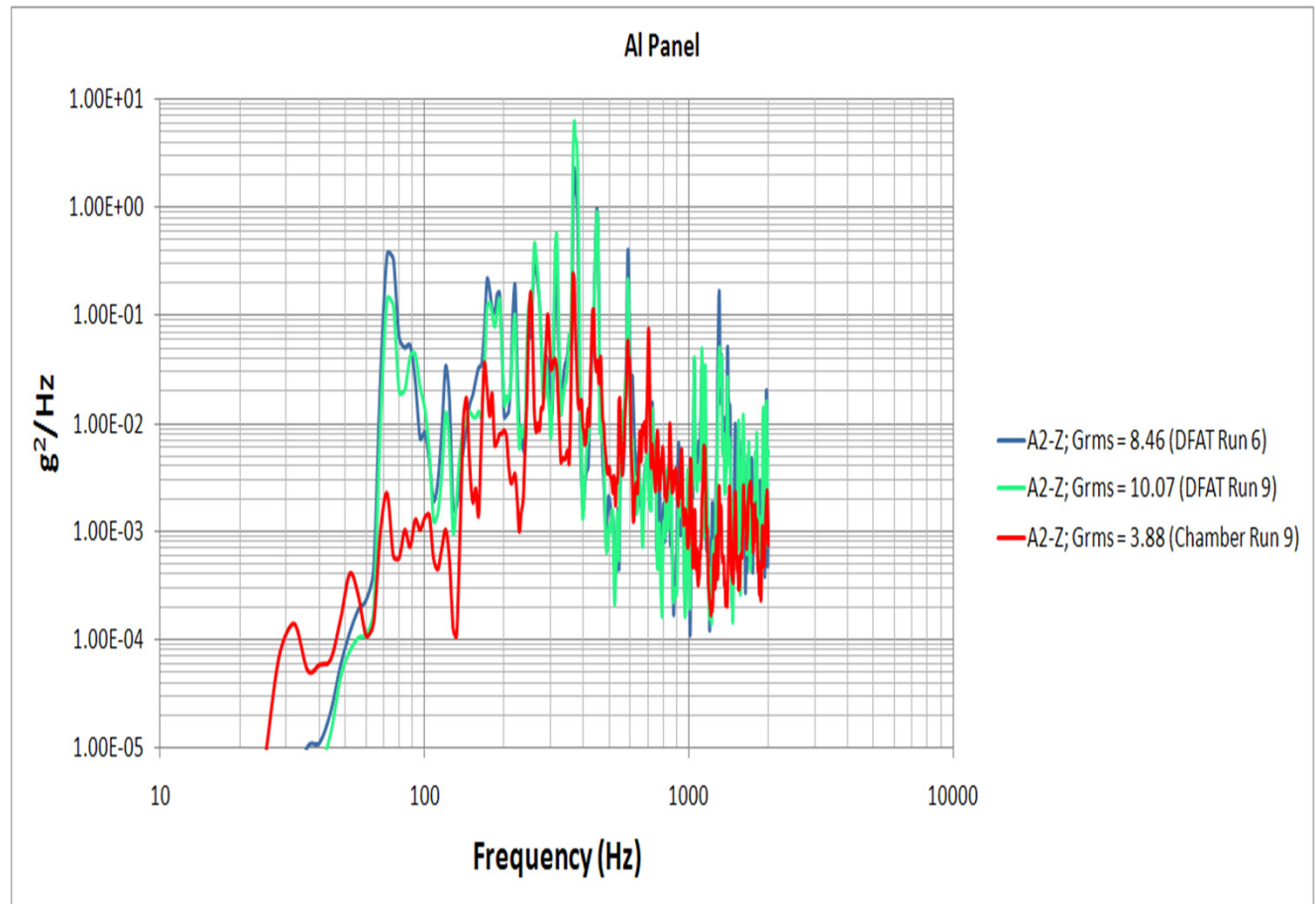
## DFAT :

- Two distinct Acoustic Standing Waves @ 100 Hz and ~250 Hz
- Significantly Higher Average SPL

**The average SPLs measured in DFAT and RAT from a microphone array are significantly different**

## JPL Demo Test: AI Panel Responses DFAT and RAT Comparisons (SISO Control Scheme)

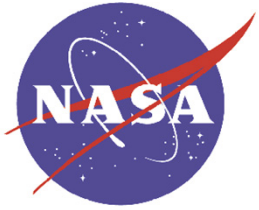
**The panel responses are much higher in the DFAT for this cases than are in RAT testing (6-8 dB grms). At ~72 Hz, the responses are ~ 20+ dB higher!**





# Summary and Recommendations

- Improvements in DFAT method have been made within the past 3 years
  - The improvements made so far are mainly in controlling sound field using Multi-input-multi-output scheme
  - MIMO control scheme helped reduce the spatial variation observed using the SISO control scheme
    - Improvements are still needed to reduce spatial variations in mid-frequency range
- Despite improvements made in DFAT, the acoustic field is much more complex with not enough resources allocated to characterize
  - Acoustic wave interference patterns and acoustic standing waves
  - Direct vs. non-direct acoustic waves
- Acoustic standing waves/structural mode coupling occurs both in DFAT and RAT qualification testing of flight hardware
  - Significantly increases structural responses when such coupling occurs
  - The knowledge of standing waves and structural modes for safe acoustic testing important before a sensitive hardware is exposed to the acoustic field
- Recommendations
  - Analytical/numerical modeling to understand and characterize the DFAT acoustic field, in particular to differentiate acoustic standing waves from interference patterns
    - Prior to testing, utilize BEM analysis to design test setup and optimize the field for safe acoustic testing that meets the requirements
  - DFAT Handbooks
    - IEST (First DRAFT is ready) and NASA (under preparation).



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# Thank you

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